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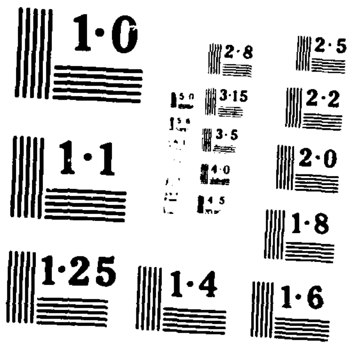
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A Fortran Code for the Calculation of Probe Volume Geometry Changes in a Laser Anemometry System Caused by Window Refraction

Albert K. Owen
Propulsion Directorate
U.S. Army Aviation Research and Technology Activity—AVSCOM
Lewis Research Center
Cleveland, Ohio

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A FORTRAN CODE FOR THE CALCULATION OF PROBE VOLUME GEOMETRY CHANGES IN A LASER ANEMOMETRY SYSTEM CAUSED BY WINDOW REFRACTION

Albert K. Owen
Propulsion Directorate
U.S. Army Aviation Research and Technology Activity - AVSCOM
Lewis Research Center
Cleveland, Ohio 44135

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SUMMARY

A computer code has been written which utilizes ray-tracing techniques to predict the changes in position and geometry of a laser doppler velocimeter probe volume resulting from refraction effects. The code predicts the position change, changes in beam crossing angle, and the amount of uncrossing that occur when the beams traverse a region with a changed index of refraction, such as a glass window. The code calculates the changes for flat plate, cylinder, general axisymmetric, and general surface windows and is currently operational on a VAX 8600 computer system.

INTRODUCTION

The laser anemometer has provided the fluid dynamicist with a powerful tool for nonintrusively measuring fluid velocities. One of the more common types of laser anemometers, the laser fringe anemometer, divides a single laser beam into two parallel beams and then focuses them to a point in space called a "probe volume" (PV) where the fluid velocity is measured.

Many applications using this method for measuring fluid velocities require the observation of fluids through a window. Whenever light traverses a region of a different refractive index, its direction of travel is changed in a manner described by Snell's law:

$$N \sin \alpha = N' \sin \alpha' \qquad (1)$$

where

N, N' indices of refraction before and after the surface

α, α' angles between the surface normal and the light beam on either side of the surface.

With the exception of a few very specific window/optics configurations, the implications of this law to the laser probe volume when a window is inserted in the laser beam optical path between the focusing lens and the probe volume can be summarized as follows:

(1) The position of the actual probe volume will change.

(2) The beams will uncross, i.e., no longer lie in the same plane at the probe volume location.

(3) For nonflat plate windows, the crossing angle of the two beams will change.

The first result means that data will not be acquired in the desired location. The second affects the data acquisition rate by distorting the probe volume, which only exists where the beams cross. The last impacts the accuracy of the measurements taken because it is directly related to the calculation of velocity by the following equation:

$$V = \lambda f/(2 \sin(\epsilon/2)) \tag{2}$$

where

λ light wavelength

f fringe crossing frequency

ϵ beam crossing angle

In the past, most researchers have assumed that the resulting errors are small and can be ignored. The few attempts to assess the seriousness of window refraction effects (refs. 1 to 4) have, unfortunately, been concerned with special cases such as flat windows and cylinders with observations in a single plane normal to the axis of symmetry. This approach has proved reasonable in the past since windows were usually simply shaped and thin. Further, observation angles were generally near normal to the window surfaces.

A more general approach developed at the NASA Lewis Research Center to meet the needs resulting from the use of more complex window shapes and passage geometries is reported here.

A ray tracing technique which is not restricted to special cases is used to study the changes in probe volume geometry and position due to refraction effects caused by both flat and general smooth windows. This technique predicts the laser beam paths through any of four different window shapes:

(1) Flat plate windows (constant thickness)

(2) Cylindrical windows (constant thickness)

(3) General axisymmetric windows (constant thickness)

(4) General smooth windows (variable thickness)

When describing the window surfaces, the technique calculates the flat plate and cylindrical window cases analytically. The general axisymmetric case is treated analytically in the R-Θ plane and uses a cubic spline fit in

the R-Z plane where the Z axis represents the axis of window symmetry. The smooth general window case uses the cubic spline fit in both the X-Y and X-Z planes.

The technique yields the new probe volume position, the new crossing angle, and the amount of beam uncrossing (specified as both the number of probe volume fringes and the absolute minimum distance between beams).

Two separate computer programs are used. The first program generates an input data set for use by the second program. The second calculates the changes in the geometry of the probe volume. The use of a separate program allows the creation of permanent input datasets.

The following parameters may be varied to describe the case to be evaluated:

(1) Indices of refraction on both sides of the window and the window itself

(2) The window shape

(3) The assumed position of the probe volume and the actual position of the focusing lens relative to the window

(4) The orientation of the plane which contains the laser beams

(5) The beam crossing angle

(6) The laser beam wavelength

This report contains a description of the problem geometry, the method of analysis, complete information for using these programs, example input and output, and several example cases for general axisymmetric and smooth totally general surfaces.

These FORTRAN 77 programs are currently operational on a DEC VAX8600 computer. These interactive programs require a typical core memory of 86 pages and have typical CPU run times of less than 1 sec, depending upon window geometry.

GEOMETRY

A basic understanding of the window and optics geometry and the variables used to describe them is necessary to correctly use the technique explained in this report. Therefore, we will take a more detailed look at the geometries of the surfaces involved. Figure 1 provides information on the general orientation of the probe volume and lens for all windows. While most of the information presented in this figure is self explanatory, some points should be clarified.

The X', Y', Z' coordinate system shown in figure 1 has its origin at the probe volume. The X-Y-Z coordinate system, not shown in figure 1, is oriented such that the Z axis is along the axis of symmetry of the window

being described, should this window be symmetric. The axes of the X', Y', Z' coordinate system are parallel to their respective X, Y, Z axes. The origins of the two coordinate systems are not necessarily coincident.

The X axis should be oriented roughly so that the optical system bisecting line parallels the X-Z plane.

The bisecting line is defined as a line equidistant from both laser beams and lying in the plane defined by them. It connects the lens center and the original probe volume.

The original probe volume is the probe volume position that would exist if there were no window in the optical path between the focusing lens and the probe volume.

The beam crossing angle, ε, is, for all cases, the angle defined as:

$$\tan \varepsilon = |A_1 \times A_2| / A_1 \cdot A_2 \tag{3}$$

where

ε beam crossing angle

A_1, A_2 incoming laser beam vectors

The angle ϕ, not shown in figure 1, is the angle between the surface normal and the bisecting line for the flat plate window.

For all cases, the beam plane orientation angle, δ, is defined as the angle measured counterclockwise in the lens plane, made by the line connecting the two beams where they cross the lens plane and a line, Z", where Z" is a line lying in a plane formed by the Z' axis and the beam bisecting line (fig. 1).

Figure 2 shows the geometry for the cylindrical window case and additional information for describing the lens and original probe volume position. Notice that the axis of symmetry of the window is the Z-axis.

For all window cases, the lens center and probe volume position are described in the R, Z, Θ coordinate system. Neither the probe volume nor the lens center axial position are restricted to a Z equal zero requirement.

Figure 3 shows the general axisymmetric coordinate system. The window is described as a set of R-Z points that specify the window outer surface. The window inner surface is specified using a normal thickness. For this window, the thickness must be constant.

Figure 4 indicates the method in which the general smooth window is specified. Here both surfaces are specified as an array of X, Y, Z points in space. There are no restrictions on window thickness in this case. The numbers in parentheses indicate the array locations of the points.

The specific restrictions to the geometries described above are:

(1) Surfaces must be smooth and smoothly changing.

(2) For all general axisymmetric surfaces, surface slopes in the Z direction, DX/DZ, must remain less that 45° and DY/DZ must remain less than 45° for all general smooth surfaces.

(3) The Z axis is defined as the center of rotation for the cylindrical and general axisymmetric surface.

(4) Rl, the lens radial position, should be greater than Rpv, the probe volume radial position, and greater than Ro, the window outer radius and Rpv should be less than Ri, the window inner radius (fig. 2).

METHOD OF ANALYSIS

The code uses a simple ray tracing technique for the necessary calculations. To accomplish this, the initial ray direction cosines and the points in space where the beams cross the lens plane are calculated.

Then, from the window surface information, the point of interception of each beam with the upper or outer window surface and the surface window normal at that point are calculated. Snell's law is applied to each beam as it crosses the surface. The same procedure is then applied to find the interception of the beam and the lower or inner window surface.

With the position and the direction cosines of the two beams at the inside of the window, the calculation of minimum crossing distance, crossing angle, and the point of nearest approach become relatively straightforward geometry problems.

Of importance is how the beam/window interception point and the surface normals at the interception point are calculated.

The following section discusses the methods used to determine the point of beam/window interception and the window outward surface normal at the beam-window interception point for each of the four window types this computer code solves.

At the point of intersection of the laser beams and surfaces, the laser beams and the surface normals can be described using direction cosines in the following way:

$$V = (\cos \alpha)i + (\cos \beta)j + (\cos \gamma)k \tag{4}$$

where

V incoming laser beam vector

α, β, γ direction angles between the vector and the X, Y, Z axes

for each incoming laser beam and

$$N = (\cos \upsilon)i + (\cos \zeta)j + (\cos \sigma)k \quad (5)$$

where

N outward surface normal

ν,ζ,σ direction angles between the vector and the X, Y, Z axes

for each outward surface normal (figs. 5 and 6), where both are defined as unit vectors.

The angle between these two vectors is simply the arc cosine of the dot product.

$$\cos^{-1}\phi = V \cdot N = \cos \alpha \cos \upsilon + \cos \beta \cos \zeta + \cos \gamma \cos \sigma \quad (6)$$

Using a simple ray tracing analysis and Snell's law; the direction of the ray after crossing the surface can be determined by (ref. 5):

$$V' = (n/n')V + (b/n')N \quad (7)$$

where n is the index of refraction on the incoming side of the surface, n' is the index of refraction after crossing the interface, N is defined by Eq. 5, and b is:

$$b = n' \cos \phi - n \cos \phi' \quad (8)$$

and ϕ' is given by

$$\cos \phi' = (n'^2 - n^2 + n^2 \cos^2 \alpha)/n' \quad (9)$$

Using these equations, a method for describing the window surfaces in space, and the window surface normals; the path of each beam can be traced.

The window surfaces and their surface normals are described differently for each of the four types of surfaces.

The flat window surfaces are described using the equation of a flat surface:

$$(X - X1)/\cos \nu = (Y - Y1)/\cos \zeta = (Z - Z1)/\cos \sigma \quad (10)$$

where

X,Y,Z surface coordinates

X1,Y1,Z1 a specified surface point

ν,ζ,σ surface normal direction cosines

A flat surface can be specified by any three points not in a straight line. The cross product of any two unit vectors connecting these points provides the surface normal and its direction cosines. Since the surface is flat, the surface normal has a constant direction.

The cylindrical and general axisymmetric windows are described using the equation:

$$R^2 = X^2 + Y^2 \tag{11}$$

where

R constant radius for a cylinder and

R f(z) for the general axisymmetric case and f(z) is specified by a series of R-Z points

X,Y surface coordinates

The necessary direction cosines for a cylinder are also relatively straight forward calculations. The slope of the circle at any point can be obtained by taking the derivative of X with respect to Y. This information, coupled with the fact that the direction cosine with respect to the axis of symmetry is zero provides all the necessary information.

To approximate the unknown R-Z relationship in the general axisymmetric case, the program makes use of a cubic spline fit subroutine described in reference 6. It solves a tridiagonal matrix given in reference 7. The inputs are a series of R-Z values. It should be noted that the spline subroutine requires that the end point condition of the second derivative at either curve end point be specified. The input default gives an end point second derivative of one half the second derivative of the adjacent spline point. Care must be taken to insure the input points accurately describe the surface, that the surface is smooth and that the end point second derivatives are not greatly in error. Inaccuracies occur in the solution when the surface described has slopes approaching 90° and surfaces of this type should be calculated using the general surface routine with an appropriate coordinate rotation for the geometry.

Output from this cubic spline fit at the desired Z location includes the value of the radius and both the first and second derivatives of radius with respect to axial position. To solve for the intersection between the window surface and incoming laser beam, the incoming beam is first described as a function of radius and axial position. An iterative procedure is then used to

find the R-Z interception point of the incoming ray and the surface. The desired solution accuracy for the iterative procedure is an input value.

At the calculated intersection point, the slopes of the general axisymmetric surface are known:

$$dR/dZ \text{ and } dX/dY$$

However, we are interested in the surface normal direction cosines (fig. 5): $\cos \nu$, $\cos \zeta$, and $\cos \sigma$. The last is directly available since:

$$\tan \sigma = -1/(dR/dZ) \tag{12}$$

Now, recalling that:

$$1 = (\cos^2\nu) + (\cos^2\zeta) + (\cos^2\sigma) \tag{13}$$

and that, since dX/dY is known

$$\tan \xi = dX/dY \tag{14}$$

Now,

$$\cos \nu = b/s \tag{15}$$

and

$$s = (a^2 + b^2 + d^2)^{1/2} \tag{16}$$

and realizing that

$$a = b \tan \xi \quad \text{and} \quad d = b \tan \kappa \tag{17}$$

where a, b, c, and d are distances defined in figure 5(b) we can write

$$\cos \nu = b/(b^2 + b^2\tan^2\xi + b^2\tan \kappa)^{1/2} \tag{18}$$

or

$$\cos \nu = 1/(1 + \tan^2\xi + \tan^2\kappa)^{1/2} \tag{19}$$

and

$$\cos \zeta = (1 - \cos^2\sigma - \cos^2\nu)^{1/2} \tag{20}$$

The general surface solution follows the same logic; the difference being that no analytical expressions exist to describe the surface. The surfaces are described by an array of X, Y, Z coordinates. These coordinates should form a roughly rectangular mesh (fig. 4). The method uses a linear interpolation scheme (ref. 6) to determine an approximate ray-surface intersection point. Once a "near solution" point is found, the method calls the spline fit routine in the two orthgonal directions (Y and Z in fig. 6) to calculate a more accurate interception point. The subroutine checks the interception points and the changes in slope using the spline fit in both orthogonal directions. Should they be outside the input tolerances, an error message is printed. However, the calculation continues.

The surface normal is calculated in a manner similar to that of the general axisymmetric case. The differences are that the outputs from the cubic spline fits include:

$$dX/dY \text{ and } dX/dZ$$

Thus

$$\tan \xi = 1/(dX/dY) \tag{21}$$

and

$$\tan \kappa = 1/(dX/dZ) \tag{22}$$

Now

$$\tan \sigma = c/d \tag{23}$$

and

$$c = (a^2 + b^2)^{1/2} \tag{24}$$

where

$$a = b \tan \xi \tag{25}$$

and

$$d = b \tan \kappa \tag{26}$$

where a, b, c, and d are distances defined in figure 6, so

$$\tan \sigma = b(\tan^2\xi + 1)^{1/2}/(b \tan \kappa) \tag{27}$$

or

$$\tan \sigma = (\tan^2\xi + 1)^{1/2}/\tan \kappa \tag{28}$$

Once the value of σ can be determined, ν and ζ can be evaluated in a manner similar to the general axisymmetric case where:

$$\cos \nu = 1/(1 + \tan^2\sigma + \tan^2\nu)^{1/2} \tag{29}$$

and

$$\cos \zeta = (1 - \cos^2\sigma - \cos^2\nu)^{1/2} \tag{30}$$

It is possible to describe the interception point and the surface normals at that point. Now the changes in probe volume geometry can be calculated.

TOLERANCES

The computer program requests user input of four tolerances. There are two types of tolerances. The first type specifies how near parallel to a coordinate axis a direction vector need be to be considered parallel to that axis. This simplifies some calculations and can improve accuracy by eliminating divisions by numbers near zero. The other type of tolerance is used to specify the solution accuracy of the window surfaces during the calculations of the general smooth windows.

All requested tolerances have default values.

The first tolerance requested, 'TL1', is used during the calculation of the direction cosines of the nonrefracted laser beams. In later calculations, divisions by the direction cosines of the laser beams are required. The tolerance 'TL1' specifies at what point the beam is considered to be parallel to a coordinate axis. This insures that division by a very small number during the calculation of the beam surface intercept point does not occur.

Tolerance 'TL2' restricts the potential error generated in the solution of the general surface outward normal. Small errors in these values can make noticeable differences in the final solution. To limit the potential error, the slopes of the four points bracketting the proposed interception point are calculated. The changes in the slopes in the two coordinate directions are calculated and these changes are required to be less than 'TL2.' This effectively limits the maximum possible error in the surface normal of the intercept. If this convergence criteria is not met, a finer grid describing the window surface is generated and the calculation is repeated.

The third tolerance, 'TL3', restricts the possible error of the intercept point of the incoming light beam and the window surface. The intercept point calculated using a linear interpolation between the points bracketting the intercept region is compared with the intercept point calculated using a cubic spline interpolation. If the difference is within the tolerance 'TL3' the program continues. If this criteria is not met, a finer grid describing the surface is generated and the intercept calculation is repeated.

The last input tolerance, 'TL4', is similar to the first since it specifies whether or not a direction cosine is near parallel to the X-axis or lies in the X to Y or X to Z planes. Those special cases allow simplified calculations and use of the simplified calculations insures that division by a very small number does not occur.

All default tolerances result in sufficiently accurate solutions for the types of window in use at the Lewis Research Center. For comparison, note that the typical window at Lewis Research Center might have a change in slope of 2.3° per centimeter in a direction perpendicular to the incoming Laser Beam.

EXAMPLES

A number of test cases for the flat plate and cylindrical window were run and the results are available in reference 8. A comparison of output with an unpublished algorithm and also with hand calculations show an exact agreement with both the flat plate and simple cylinder test cases.

Since the window shapes for the general axisymmetric and smooth general windows can only be approximated, ideal comparisons are difficult. In results not given here, the use of the general axisymmetric technique to calculate window effects of a cylindrical window results in an identical solution with the cylindrical window solution and using the smooth general technique to calculate the effects of a flat plate window also results in an exact comparison with the flat plate solution.

The general axisymmetric case was also run to calculate the window effects of an actual compressor window. Figure 7 shows the input geometry. The bisecting line is moved out of the X to Z and X to Y planes. This general axisymmetric case was also compared with two outputs run using the general smooth window algorithm. These two general smooth cases varied only with respect to the orientation of the window and lens geometry to the coordinate system. The first orientation run was similar to the general axisymmetric orientation shown in figure 7. The second orientation is shown in figure 8 and simply results from rotating the problem geometry about the Y-axis. The

window geometry is given in Table I(a) and the other relevant parameters are given in Table I(b).

A comparison of outputs, provided in figures 9 to 11, showed very good agreement between the three cases.

Figure 9 shows the uncrossing results, in fringes, versus δ for the three cases. Maximum difference between cases is slightly over three fringes at δ equal 90°. This is a relatively large number of fringes; however, it occurs in a geometry where the total uncrossing is a minimum. Over most of the range of comparison, the difference is less than two fringes. From a practical standpoint, the agreement for all three cases is excellent.

Figure 10 shows the change in beam crossing angled versus δ for the three test cases. Once again, the agreement is very good with the maximum difference in the three configurations less than 0.017°. This maximum difference results in velocity errors of less than 0.3 meters per second. Note, however, that the maximum calculated velocity error due to the change in crossing angle from refraction effects is calculated to be about 1 meter per second for these test cases.

Figure 11 shows the change in probe volume position for each of the three cases. The figure shows the relative movement in each coordinate direction and the total relative movement. Movement is defined as the change in probe volume position from the position it would occupy if there were no intervening window. Relative movement is that distance divided by the window thickness. Agreement is excellent for total movement and X direction movement with a maximum difference being less than 10 percent or, in absolute differences, 0.00635 cm (window thickness of 0.3175 cm). The Y and Z direction movements show excellent agreement between the two test cases with the same window/coordinate system orientation. However, when the window surface is rotated to an orientation that is not approximately in the Y to Z plane, the agreement is not as good. Nevertheless, for both directions, the total difference in movement between test cases is only about 0.00225x window thickness or about 7.15×10^{-4} cm for a 0.3175 cm thick window. This is equivalent to less than one third of the probe volume diameter.

This set of test cases demonstrates two important points. The first is to use the surface description that most accurately reflects the actual window geometry. If the window can be described using a general axisymmetric surface, this is the most desirable method of input. If the window can be specified as a flat plate or simple cylinder, these are the most desirable datasets. The second point is that, if the surface to be considered is best described as a smooth general surface, the orientation of the window surface normal should be kept as nearly parallel to the X-axis as possible.

CONCLUSIONS

A FORTRAN computer program has been developed to solve for the movement, beam uncrossing, and bisecting angle change of a probe volume of a laser fringe anemometer when it must traverse an intervening region of different refractive index.

This program analytically solves for a flat plate window or a cylindrical window. It uses a cubic spline curve fit and an iterative procedure to solve for a general axisymmetric and a general surface window.

The comparison of results for all window surface routines is good provided the surfaces are well behaved and well described in the region where the beams intersect the window.

The assumption that window refraction effects on the probe volume are negligible cannot be supported in cases where complex window geometries are being used.

APPENDIX A

INPUTS AND OPERATION OF THE PROGRAMS

As currently configured, two separate computer codes are necessary for a complete solution. Both programs are interactive and require user inputs. Both programs use FORTRAN coding for the terminal interactive operations and for manipulating the necessary data files.

The first program sets up an input data set to be run. This allows a permanent file of different input data sets to be maintained. The input data file structure is shown in figure A1. A glossary of terms is provided in Appendix B.

Lines 4 through 6 are optional. Should nop2 be set to zero, the program will generate output for beam plane orientations every 10° from 0 to 170. In this instance, no entries need to be made for lines 4 through 6 and the user will be immediately prompted for line 7.

Starting with line 9, the input varies depending on the nature of the window to be described. For a general window, the "upper" or outer surface variables are read in one at a time increasing in the 'Y' or leading index first, as shown in figure 4. When finished with the window upper surface, continue with the lower or inner surface.

Inputs for the flat plate are done in the same manner except that only four points per surface (total of eight for the window) should be entered.

For the cylindrical window, the only input past card 8 is the outer surface radius.

For the general axisymmetric window, type in the number of Z to R points to describe the upper surface and the Z to R values.

Figure A2 shows the coordinate system and variables used to specify the problem geometry. Angles should be input as degrees and distances can be specified in any consistent set of units.

The second, or beam uncrossing program requires the file name containing the input data.

The beam uncrossing program then queries the operator to insure that the input parameters are correct. This also allows modification of all inputs other than the basic window geometry.

APPENDIX B

INPUT DICTIONARY

All integer fields are I5 format and all real fields are F10 format.

delta (1-nop2)	an array of angles describing the angle between the plane the two incoming beams lie in and a plane containing the lens center-z axis (axis of rotation), see figure A2b, in degrees.
D2XDY2	specifies the magnitude of the second derivative at the end points of the cubic spline fit when the window to be modeled is a general axisymmetric or general smooth window. (default=.5)
eps	the bisecting angle of the beams in degrees
iy1, iy2	number of points in the "y" direction to describe surfaces 1, 2; 01 for cylindrical, 02 for flat plate, and 10(max) for general surface
iz1, iz2	number of points in the "z" direction to describe surfaces 1, 2; 02 for flat plate, 10(max) for general surface
n1, n2	index of refraction of the medium before and after traversing the window; (default = 1.00029, air)
nr	number of Z to R coordinate pairs used to describe a general axisymmetric window
nt	index of refraction of the window; (default = 1.6, nominal glass)
nop1	flag to define the type of window to be input; 0 - general surface, 1 - flat plate, 2 - cylindrical, and 3 - general axisymmetric
nop2	defines whether the series of angles (delta) is defaulted or specified; 0 - defaulted, gives delta increments of 10° from 0 to 170, 1 to 18 indicates nop2 number of delta angles to be input
rc1(1-nr)	outer surface radius, general axisymmetric or cylindrical surface.
r1	distance from the center of the focusing lens to the axis of rotation (z axis)
rpv	distance of the probe volume (lens focal point assuming no intervening window) to the axis of rotation (z axis)

thk	window normal thickness; not used for general surface input.
thl	angle between the x axis and a perpendicular line connecting the z axis and the center of the focusing lens
thpv	angle between the x axis and a perpendicular line connecting the z axis and the probe volume (focal point of the lens)
tl1	tolerance used in subroutine 'ppos.' Defines whether or not the plane in which the two incoming laser beams lie is parallel to any coordinate plane. This specifies the nature of the calculation of the beam/focusing lens plane intercept calculation. (default is .0017rad)
tl2	tolerance in subroutine 'sfin'. Determines a successful solution to the general surface/laser beam intercept. This criteria restricts the maximum error between the actual surface normal direction and the calculated value. Default is set to cos (angle error)<.01.
tl3	tolerance in subroutine 'sfin'. Determines a successful solution to the general surface/laser beam intercept. This is a limit between the difference in calculated intercept points using the 'linint' (linear interpolation) approximation of the window surface and the 'splint' (spline interpolation) approximation of the window surface. It is assumed that when the difference is less than (tl3*thk), the surface description is accurate for an acceptable answer. Default is 0.0015.
tl4	tolerance in subroutine 'sfin'. Determines if any surface direction vector is near parallel to the x-axis or liens in the X to Y or X to Z planes. Maximum off parallel or out-of-plane error for the direction cosine is tl4. Default is .0017.
x1,y1,z1(1-iy1,1-iz1)	x, y, z coordinates describing the upper surface for the flat plate or general window case.
x2,y2,z2(1-iy2,1-iz2)	x, y, z coordinates describing the lower surface for the flat plate or general surface case
wvl	Laser beam wavelength in Angstroms. Used for calculating the uncrossing in fringes. (default=5145A)
zcl(1-nr)	z coordinates (along the axis of symmetry) corresponding to rcl for the general axisymmetric case
zl	axial distance of focusing lens center
zpv	axial distance of probe volume (focal point)

APPENDIX C

SYMBOLS

f prove volume fringe crossing frequency

n index of refraction

N outward surface normal at point of laser beam/surface intersection

V fluid (particle) velocity vector

V_i laser beam direction vector, $i = 1$ or 2

σ, β, γ direction angle for incoming laser beam

ν, ζ, σ direction angles for outward surface normal vector (fig. 5 and 6)

λ light wavelength

K angle between a surface tangent line in the X to Z plane and the Z axis (fig. 5 and 6)

ξ angle between a surface tangent line in the X to Y plane and the Y axis (fig. 5 and 6)

ε beam crossing angle in probe volume

ϕ angle between the outward surface normal and the incoming laser beam

Superscript

' indicates the region after the laser beam has crossed the surface boundary

" indicates a coordinate system centered on the surface/ray intercept point. Used in figures 4 and 6.

APPENDIX D

SAMPLE INPUTS AND OUTPUTS

Figures D1 through D4 show the sample inpucs for flat plate, simple cylinder, general axisymmetric, and general smooth windows, respectively. In these figures, all user inputs are underlined and an asterisk is found at the right hand margin of these lines.

Notice that the data set up program allows the option to change any input data line. The line number of the line that is to be changed is typed in, then the entire line is retyped.

Figure D5 shows a sample output from the main optics code. This output is self explanatory.

APPENDIX E

WARNING MESSAGES

A number of warning messages may be printed during the course of a calculation. They are, for the most part, only advisory in nature with the calculation continuing. However, they may indicate an error in the input data. The possible warning messages are:

1. "WARNING: FROM RTRACE, INTERNAL REFLECTION OCCURS IN THIS CONFIGURATION."

It is possible for an optics window configuration to occur where the beam leaving the window intercepts the window surface at an angle greater than Bragg's angle. Should this occur, an internal reflection of the beam will occur. The calculation stops and output from this configuration should be considered incorrect. This situation should only occur with general smooth and general axisymmetric windows.

2. "WARNING: FROM LINT, LINES DO NOT CROSS IN SPACE."

This warning is printed out when calculations indicate that the two incoming beams lie in the same plane but intercept point calculations do not indicate the beams cross. This message indicates an input data error.

3. "WARNING: FROM CYLINT, LINE DOES NOT INTERCEPT CYLINDER WALL."

This message indicates an input geometry where the beams do not intercept the cylinder window outer surface. This message indicates an input data error. Calculation terminates.

4. "WARNING: FROM CYLINT, THE CALCULATIONS ON Z POSITION DO NOT AGREE."

This message indicates an input data error or severe geometry constraints such as an intercept near the surface tangency point or an excessive ϕ. Calculation continues.

5. "WARNING: FROM CYLINT, CALCULATED INTERCEPT X AND Y DOES NOT LIE ON R. ALTERNATE CALCULATION STARTED."

This message indicates severe geometry constraints where the surface intercept point lies near the surface tangency point. The alternate calculation should provide greater accuracy for this geometry. Calculation continues.

6. "WARNING: FROM AXI, NO CONVERGENCE IN 'AXI'."

The calculation of the intercept point of the general axisymmetric surface and an incoming ray is an iterative procedure. Should the difference between the calculated line intercept and the surface intercept point be greater than TL1 after 50 iterations, this message is printed. Calculation continues; however, the output data may be in error. This message indicates an input data error or severe surface curvature problems.

7. "WARNING: FROM SURLNT, SURLNT FAILS."

This message indicates that the intercept of the incoming light ray with the linear approximation to the general surface fails to converge within 76 iterations. Calculation continues; however, a possible problem may exist with the input surface data.

8. "WARNING: FROM SFIN, CHANGES IN THE SURFACE OR THE SURFACE NORMAL ARE RAPID, SFIN DOES NOT CONVERGE. SOLUTION ACCURACY IS NOT GUARANTEED."

This message indicates a severe window geometry resulting in a solution which may be in error. Calculation continues.

9. "WARNING: FROM FINEE, MORE THAN ONE DIRECTION COSINE IS EQUAL TO ONE."

This message should not occur and indicates an input data error that is probably in the lens-PV geometry. Calculation terminates.

10. "WARNING: FROM FINEE, THE BEAMS ARE PARALLEL AND DO NOT CROSS."

This message indicates that the window geometry has resulted in two parallel beams. There will be no probe volume and no minimum crossing distance. Calculation terminates.

11. "WARNING: FROM FINEE, DMIN=' ', DMN=' '."

The minimum crossing distance is calculated in two ways. Should the results be different, this advisory only message is printed. A large difference in values would indicate an input data error.

REFERENCES

1. Boadway, J.D.; and Karahan, E.: Correction of Laser Doppler Anemometer Readings for Refraction at Cylindrical Interfaces. DISA Information, no. 26, Feb. 1981, pp. 4-6, 31.

2. Bicen, A.F.: Refraction Correction for LDA Measurements in Flows With Curved Optical Boundaries. TSI Quarterly, vol. 8, no. 2, Apr.-June 1982, pp. 10-12.

3. Edwards, R.V.; and Dybbs, A.: Refractive Index Matching for Velocity Measurements in Complex Geometries. TSI Quarterly, vol. 10, no. 4, Oct.-Dec. 1984, pp. 3-11.

4. Seasholtz, R.G.: unpublished Algorithm, NASA Lewis Research Center, Cleveland, OH, 1984.

5. Klein, M.V.: Optics. John Wiley and Sons, 1970, p. 57.

6. Katsanis, T.; and McNally, W.D.: Revised FORTRAN Program for Calculating Velocities and Streamlines on the Hub-Shroud Midchannel Stream Surface of an Axial-, Radial-, or Mixed-Flow Turbomachine or Annular Duct, Vol. II, Programmer's Manual. NASA TN D-8431, 1977.

7. Walsh, J.L.; Ahlberg, J.H.; and Nilson, E.N.: Best Approximation Properties of the Spline Fit. J. Math. Mech., vol. 11, no. 2, 1962, pp. 225-234.

8. Owen, A.K: Parametric Study of Beam Refraction Problems Across Laser Anemometer Windows. NASA TM-87350, 1986.

TABLE I

(a) General axisymmetric window geometry

Axial Position, cm	Outer window radial position, cm
0.	25.9842
9.398	25.9842
10.668	25.9779
12.954	25.9715
15.24	25.921
16.386	25.8159
17.0866	25.7228
18.288	25.4716
18.542	25.3949
19.558	25.1892
19.947	25.1367
20.828	25.001
22.098	24.8721
23.368	24.7783
24.638	24.7225
25.908	24.7015
28.245	24.7015

(b) Lens probe volume configuration, general axisymmetric case

Out of plane angle (Xi), deg	26.56548
Probe volume position:	
radius, cm	22.3726
axial position, cm	16.5999
angular position, deg	5.6942
Lens position:	
radial position, cm	38.1
axial position, cm	87.12708
angular position, deg	3.3399
Original (measured) beam crossing angle, cm	11.49
Window normal thickness, cm	0.3175
Window index of refraction	1.52
Laser wavelength	5145A

TABLE II. - GENERAL SURFACE TEST CASES

[Comparison between calculated and measured test case probe volume movement and crossing angle change.]

General axisymmetric test case		
Position change	Calculated	Measured
X	0.032255	0.0336
Y	.002665	.0022
Z	.00907	.00685
Crossing angle change	.0068	.001276

General smooth test case		
Position change	Calculated	Measured
X(cm)	0.04464	0.0336
Y(cm)	.00354	.0022
Z(cm)	.00011	.000685
Crossing angle change	.02054	.001276

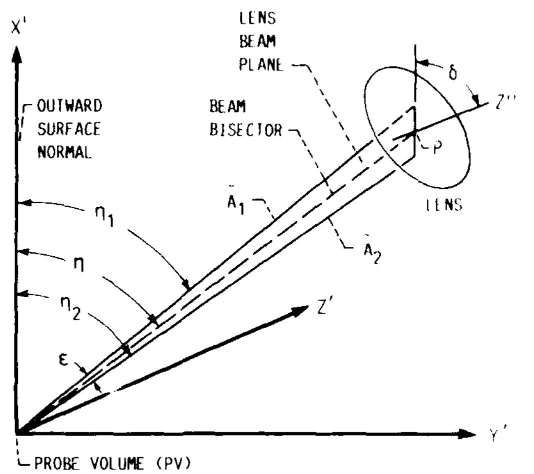


FIGURE 1. - FLAT PLATE GEOMETRY AND NOMENCLATURE.

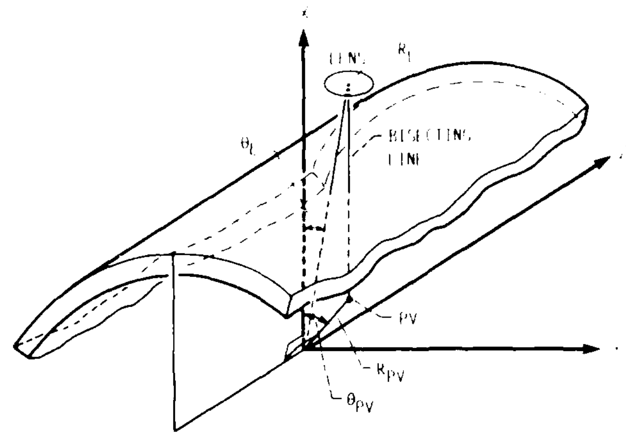


FIGURE 2. - SIMPLE CYLINDER GEOMETRY AND NOMENCLATURE.

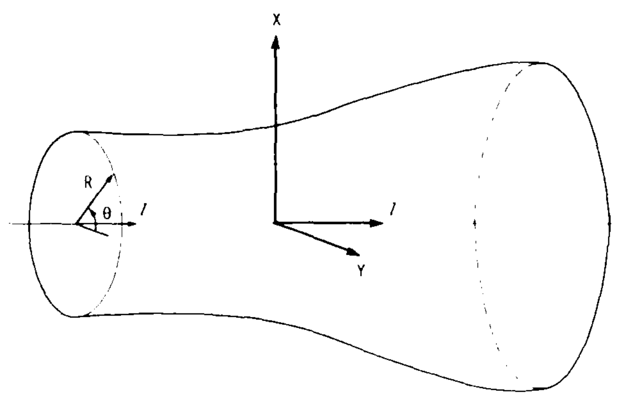


FIGURE 3. - GENERAL AXISYMMETRIC SURFACE AND IT'S COORDINATE SYSTEMS.

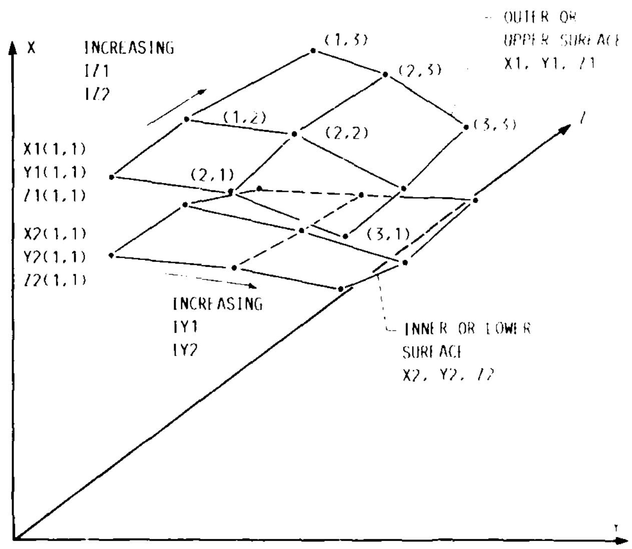
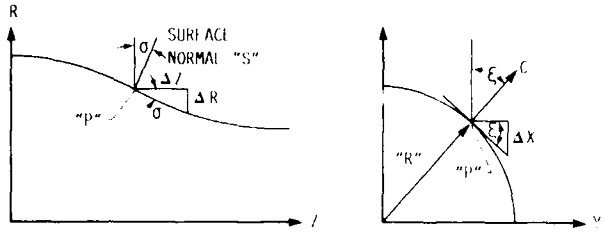
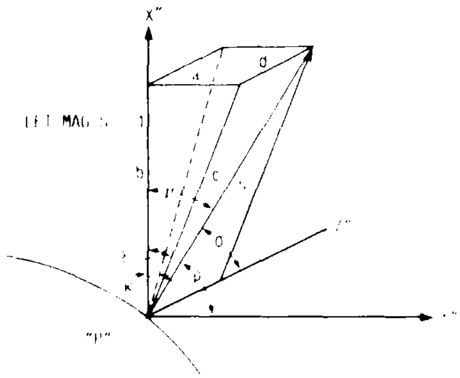


FIGURE 4. - GENERAL WINDOW INPUTS.

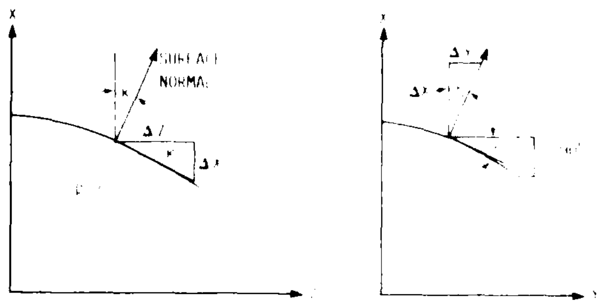


(A) SURFACE NORMALS AND SLOPES AT SURFACE (POINT "P").



(B) SURFACE NORMAL GEOMETRY AT POINT "P"

FIGURE 5. GENERAL AXISYMMETRIC SURFACE GEOMETRY
NOTE: SUPERSCRIPTS INDICATE TRANSLATED AXES



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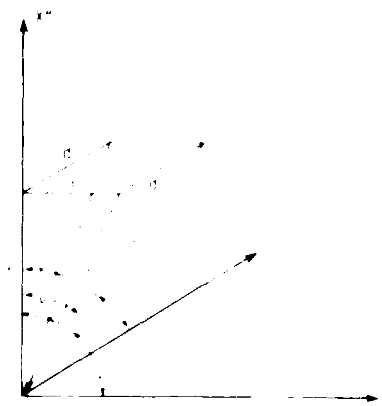
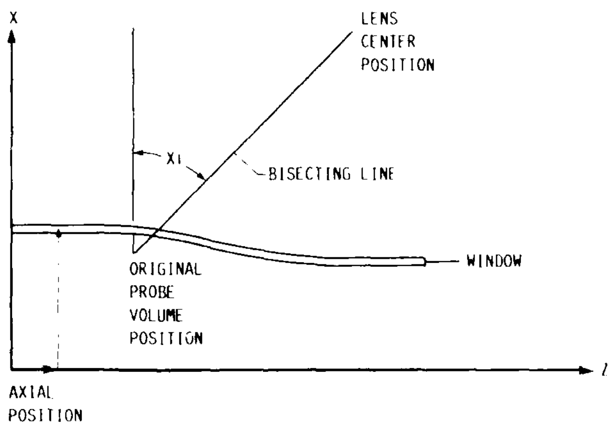
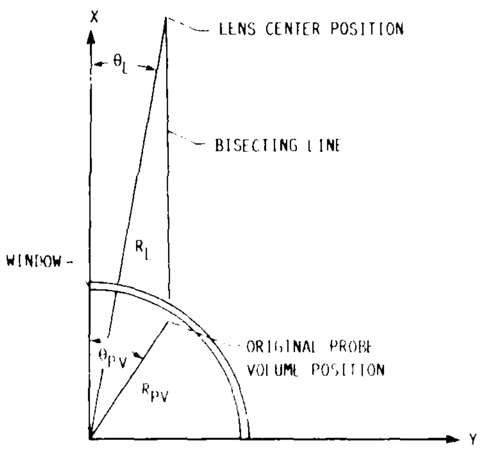


[illegible]



(A) TEST CASE GEOMETRY, R-Z (X-Z) PLANE.



(B) TEST CASE GEOMETRY, R θ (X,Y) PLANE.

FIGURE 7. - GENERAL AXISYMMETRIC TEST CASE GEOMETRIES.

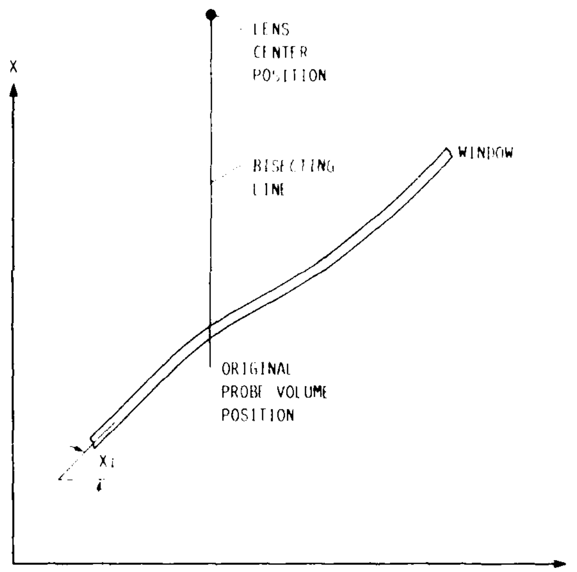


FIGURE 8. - GENERAL SMOOTH TEST CASE GEOMETRY NUMBER 2.

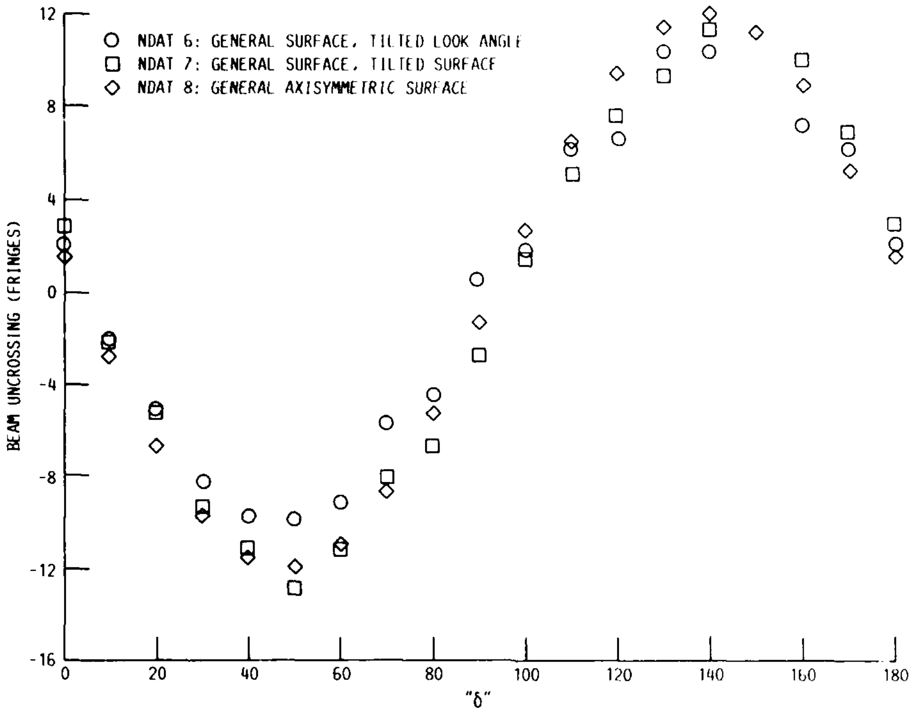


FIGURE 9. - BEAM UNCROSSING IN FRINGES VERSUS δ, GENERAL AXISYMMETRIC AND GENERAL SMOOTH TEST CASES.

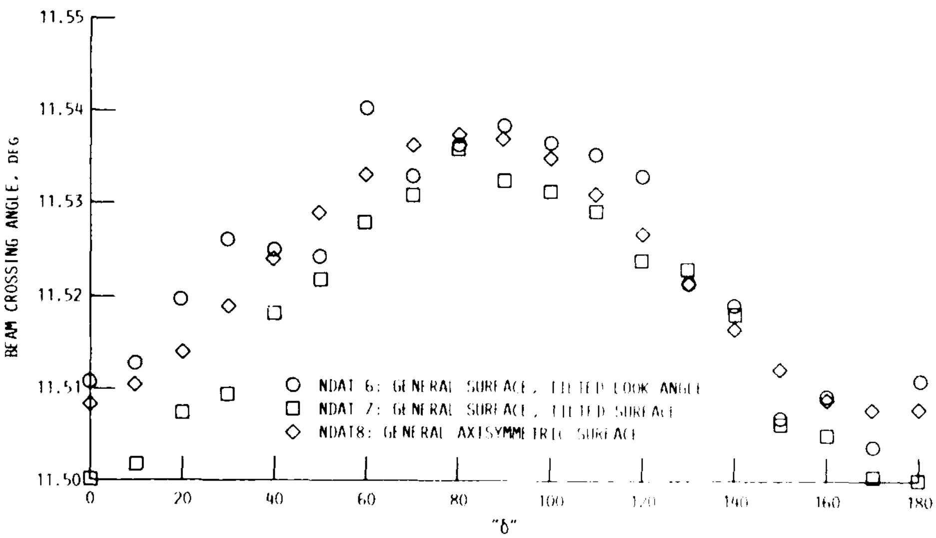
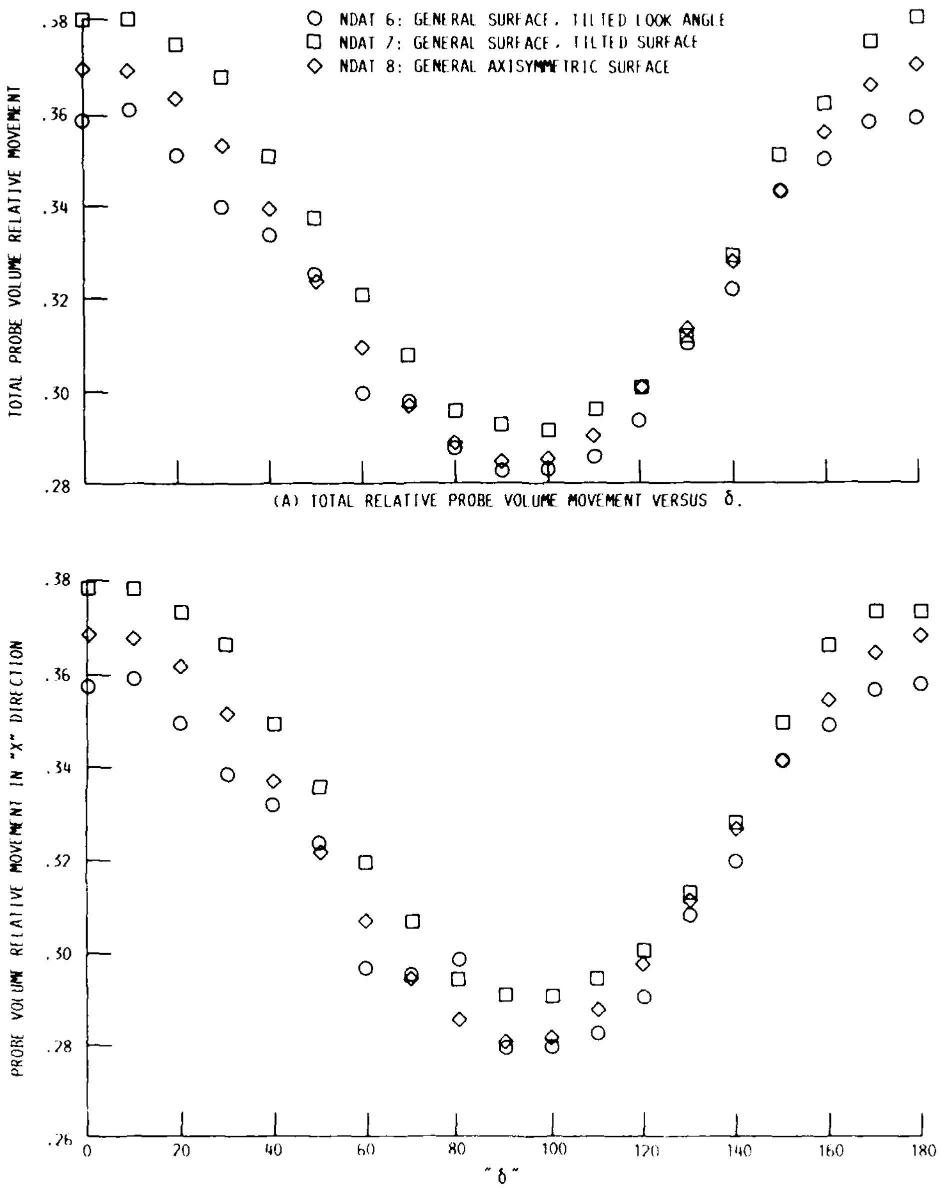
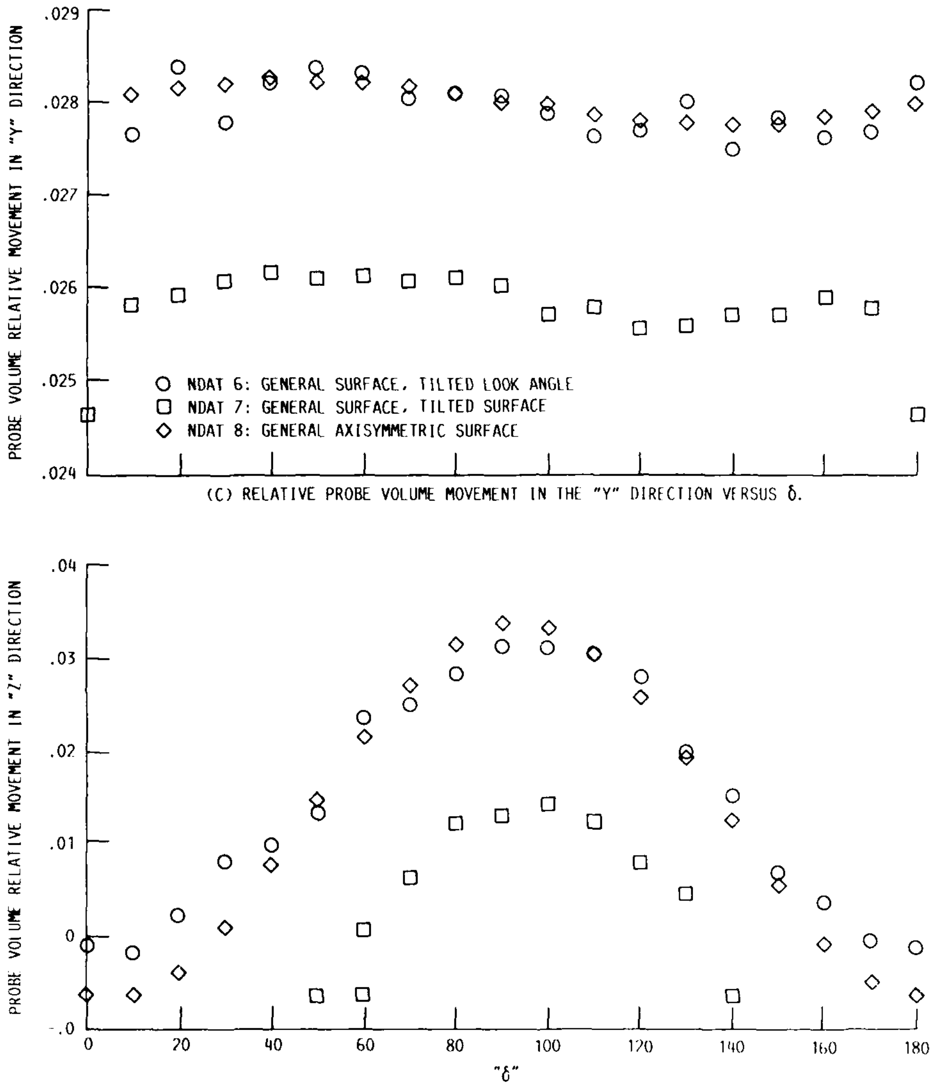


FIGURE 10. - CHANGE IN BEAM CROSSING ANGLE VERSUS δ, GENERAL AXISYMMETRIC AND GENERAL SMOOTH TEST CASES.



(B) RELATIVE PROBE VOLUME MOVEMENT IN THE "X" DIRECTION VERSUS δ.

FIGURE 11. GENERAL AXISYMMETRIC AND GENERAL SMOOTH TEST CASES.



(C) RELATIVE PROBE VOLUME MOVEMENT IN THE "Y" DIRECTION VERSUS δ.

(D) RELATIVE PROBE VOLUME MOVEMENT IN THE "Z" DIRECTION VERSUS δ.

FIGURE 11. - CONCLUDED.

COLUMN NUMBER	1-5	6-10	11-15	16-20	21-25	26-30	31-40	41-50	51-60	61-70
1	FILE NAME				(MAXIMUM OF SIX CHARACTERS)					
2	NOP 1	NOP 2	IY1	IZ1	IY2	IZ2				
3	RPV		ZPV		THPV		RL	ZL	THL	
4	DELTA (1→8)						[OPTIONAL]			
5	DELTA (9→16)						[OPTIONAL]			
6	DELTA (17-18)						[OPTIONAL]			
7	EPS		THK		NI		NT	N2	D2X/DY2	WVL
8	TL1		TL2		TL3		TL4			
9	Z1(1,1)		Y1(1,1)		X1(1,1)					
10	Z1(2,1)		Y1(2,1)		X1(2,1)					
11	Z1(3,1)		Y1(3,1)		X1(3,1)					
↓	↓		↓		↓					
	Z1(1,2)		Y1(1,2)		X1(1,2)					
	↓		↓		↓					
	Z2(1,1)		Y2(1,1)		X2(1,1)					

(A) GENERAL SURFACE OR FLAT PLATE INPUT.

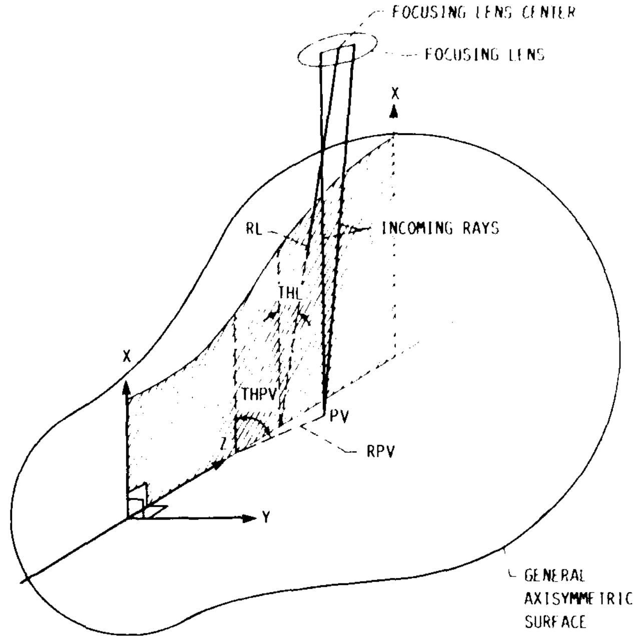
LINE NUMBER	1 - 10			
9	RCL			

(B) CYLINDRICAL WINDOW.

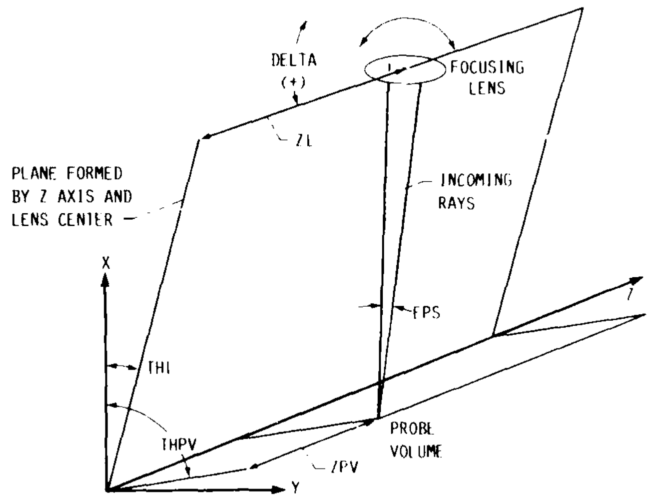
	1-3	4-10	11 - 20		
9	NR				
10	ZCL(1)		RCL(1)		
↓	↓				
	ZCL(NR)		RCL(NR)	MAXIMUM: NR = 10	

(C) GENERAL AXISYMMETRIC.

FIGURE A1. - INPUT DATA FORMAT.



(A) WINDOW GEOMETRY AND VARIABLES.



(B) LENS/PROBE VOLUME GEOMETRY.

FIGURE A2. SYSTEMS GEOMETRY.

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Report Documentation Page

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		6. Performing Organization Code
7. Author(s) Albert K. Owen		8. Performing Organization Report No. E-3820
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12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001 and U.S. Army Aviation Systems Command St. Louis, Mo. 63120-1798		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A computer code has been written which utilizes ray-tracing techniques to predict the changes in position and geometry of a laser doppler velocimeter probe volume resulting from refraction effects. The code predicts the position change, changes in beam crossing angle, and the amount of uncrossing that occur when the beams traverse a region with a changed index of refraction, such as a glass window. The code calculates the changes for flat plate, cylinder, general axisymmetric and general surface windows and is currently operational on a VAX 8600 computer system.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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